

Paleoproductivity variations in the southern Okinawa Trough since the middle Holocene: Calcareous nannofossil records

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Based on 17 AMS¹⁴C age data, we reconstructed high-resolution records of sea surface primary productivity (PP) in the southern Okinawa Trough (MD05-2908) over the last 6.8 ka BP using the calcareous nannofossil carbon isotope and the relative percent-age contents of *Florisphaera profunda* indexes. The underlying mechanism controlling the sea surface PP was then discussed. The sea surface PP, indicated by the coccolith $\delta^{13}\text{C}$ and %Fp conversional equations, decreased with some fluctuations since 6.8 ka BP. This decrease may be connected to the decreased terrigenous input resulting from the reduced East Asian Summer Monsoon (EASM) precipitation. Both the periods of 4–2 ka BP (PME) and 6.8–4.8 ka BP were characterized by relatively higher PP. The former was mainly controlled by the weakening of the Kuroshio Current, whereas the latter mainly resulted from the greater terrigenous input associated with the stronger EASM.

middle Holocene, the southern Okinawa Trough, primary productivity, calcareous nannofossil

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Relative to the ice volume changes of the high latitudes of the Northern Hemisphere, the process of low-latitude tropical influence on global climate change is mainly reflected in the controlling effects of the primary productivity of surface seawater on the global carbon cycle [1]. The CO₂ in the atmosphere is pumped into the seabed by sea surface phytoplankton through photosynthesis, and this process plays a critical role in regulating the global carbon cycle [2]. The Okinawa Trough, located under the main axis of the Kuroshio Current, has maintained a continuous sediment rate since the Late Quaternary. The high temperature, high salinity and oligotrophic Kuroshio water strongly influences the upper water structure and sea surface PP of this area. The terrigenous input from the East China Sea shelf associated with the East Asian Summer Monsoon (EASM) also impacts the sediments of the Okinawa Trough. Many studies have focused on the evolution of the paleoproductivity

of various areas of the Okinawa Trough since the Late Quaternary using different proxies, such as biomarkers [3,4], biogenic silica and organic carbon [5,6] and benthic foraminifera [7,8].

The high sediment rate of the southern Okinawa Trough has attracted the attention of many scholars [9–11]. Core ODP-1202, taken from the southern Okinawa Trough, has an average sediment rate of 325 cm/ka [12]. In this paper, the studied core MD05-2908 has a higher average sedimentation rate of 500 cm/ka since the last 6.8 ka BP. Many paleoenvironmental results have been presented from this core. Nan et al. [3] evaluated the paleoproductivity and interpreted the climatic-induced controlling factors over the past 7000 a. Li et al. [13] analyzed sediment diatoms to infer climate and paleoenvironmental changes over the past 1000 a. Li et al. [14] discussed the changes of sediment transport and source supply over the last 6.8 ka BP. As the main primary producers in the ocean, coccolithophores' vital activities are closely related to ocean hydrological

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conditions and nutrient levels [15,16]. Thus, calcareous nannofossils in the sediments are good carriers of the PP and the upper water structure. In this study, we discussed the sea surface PP changes in the southern Okinawa Trough over the last 6.8 ka BP based on the calcareous nannofossil proxies in core MD05-2908.

1 Study area

The southern Okinawa Trough region (Figure 1) has a typical subtropical monsoonal climate, where the hydrological conditions are strongly influenced by temperature, humidity and atmospheric circulation [19]. The Kuroshio Current, originating from the equatorial Pacific Ocean, flows into the Okinawa Trough through the I-Lan Ridge, transporting large amounts of heat and vapor to the mid-latitude North Pacific [20]. The sea surface temperature (SST) in the southern Okinawa Trough is obviously affected by the Kuroshio Current, with the strongest part of the Kuroshio Current accompanied by higher SSTs. The seasonal changes of the southern Okinawa Trough sea surface salinity (SSS) and the PP are affected by the monsoon process. When a stronger summer monsoon occurs, the enormous amount of runoff from the Yangtze River and Taiwan rivers induces a large amount of freshwater and nutrient input to the southern Okinawa Trough, with a resultant SSS decrease and PP increase [21].

The main sediment source of the southern Okinawa Trough is eroded material from Taiwan mountains due to

abundant summer rainfall [22]. Approximately 6–9 Mt sediments empty into the South Okinawa Trough each year through the Lanyang River of northern Taiwan. This sedimentation is usually shown as a pulse input controlled by abrupt climate events, such as earthquakes, typhoons and floods [23]. In addition, the Yangtze River inputs 240–260 Mt sediments to the East China Sea each year [24], and a small portion of suspended material from the Yangtze River and shelf deposits move into the southern Okinawa Trough through the coastal current [25]. The southeast side of Cotton Valley and the North Mien-Hua Canyon is the transportation channel of sediment from the East China Sea shelf to the southern Okinawa Trough [26].

2 Materials and methods

The piston core MD05-2908 used in this study was recovered from the southern Okinawa Trough (northeast of Taiwan, 24°48.04'N, 122°29.35'E, water depth 1276 m) during the IMAGES XIV, MD-147-Marco Polo 2 cruise of the R/V Marion Dufresne of the French Polar Institute (IPEV) (Figure 1). The 34.16-cm-long core is mainly composed of homogenous dark gray hemipelagic clay and fine silt-sized sediments without evidence of turbidites or mass redeposition. The 0–979 cm section is dark gray clay, and the 979–3416 cm section is black-grey silty clay containing a plurality of coarse sand layers.

A stable isotope analysis of the coccoliths was performed with 420 samples at 8 cm intervals. For the experimental methods, refer to Liu et al. [27]. After processing, the samples were analyzed using a MAT252 gas mass spectrometer at Institute of Earth Environment, Chinese Academy of Sciences. The analysis precision for coccolith $\delta^{13}\text{C}$ was 0.08×10^{-3} . The relative percentages of the lower photic calcareous nannofossil species *F. profunda* were analyzed using 203 samples at 10–18 cm intervals. Qualitative analysis was performed at 1600× magnification using a Leica polarizing microscope at the Key Laboratory of Marine Geology and Environment, Institute of Oceanology, Chinese Academy of Sciences. Counts and identifications were performed on permanent slides mounted with Canada balsam. At least 300 coccoliths were counted for each slide, and the relative percentages of *F. profunda*: $F.p\% = (\text{number of } F. profunda / \text{total coccolith number}) \times 100$.

The age model of core MD05-2908 was obtained by linearly interpolating between 17 ^{14}C dating points [14]. The 34.16-cm-long core spans a continuous paleoceanographic history of the past 6790 cal a BP and provides a high-resolution record of the paleoclimate change since the middle Holocene. The sedimentation rates varied widely, from 0.18 to 2.12 cm/a, with an average of 0.50 cm/a. The average resolution for the coccolith stable isotope analysis was higher than 17 a, and 34 a for the calcareous nannofossil analysis respectively.

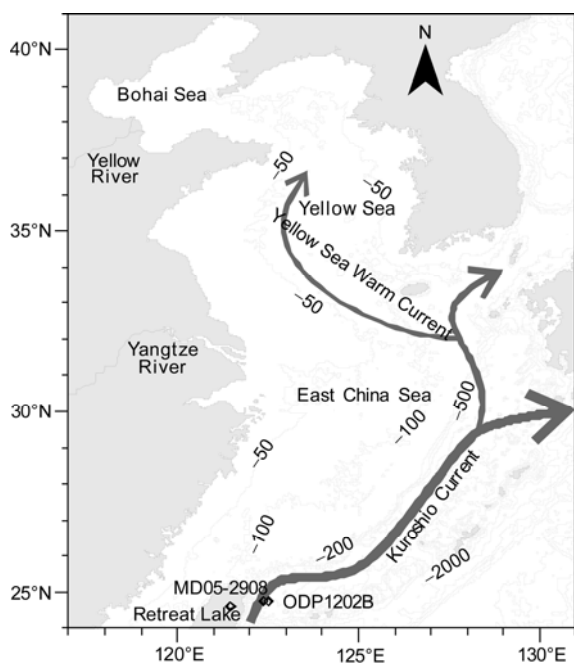


Figure 1 Location map of core MD05-2908 and the other cores discussed in this study. ODP-1202 [12], Retreat Lake [17] and Kuroshio Current [18].

3 Results and discussion

3.1 Variations of *F.p*% and coccolith $\delta^{13}\text{C}$ in core MD05-2908 over the last 6.8 ka BP

As shown in Figure 2(a) and (b), the *F.p*% and coccolith $\delta^{13}\text{C}$ changed from 30% to 58% and from -2.34‰ to -0.14‰ , with average values of 44% and -0.90‰ , respectively. The *F.p*% was lower during 6.8–4.8 ka BP, with an average value of 42%, and the coccolith $\delta^{13}\text{C}$ was higher (average value of -0.66‰) during this stage. After 4.8 ka BP, the coccolith $\delta^{13}\text{C}$ increased first, then decreased and increased again, contrary to the variations of *F.p*%. The coccolith $\delta^{13}\text{C}$ showed relatively higher values during 4–2 ka BP, with an average value of -0.80‰ , which is slightly less than at the 6.8–4.8 ka BP stage. The *F.p*% was relatively lower during 4–2 ka BP, with an average value of 44%.

3.2 PP variations in the southern Okinawa Trough over the last 6.8 ka BP

Coccolithophorids grow and calcify only in the euphotic layer and therefore exhibit surface water isotopic characteristics. In the mid-1970s, scholars [28] explored the potential applications of the stable isotope composition of coccolithophorids in paleoceanographic studies. Goodney et al. [29] proposed that sea surface PP could influence the $\delta^{13}\text{C}$ of coccoliths from the study of carbon isotopes of recent coccoliths from Indian Ocean core-tops. Recent results of Quaternary sediments from the southern South China Sea, the western Pacific warm pool and the western Philippine Sea showed that coccolith $\delta^{13}\text{C}$ could qualitatively reflect the sea surface PP, and lower $\delta^{13}\text{C}$ values indicate lower PP values [27,30–32].

The coccolithophore *F. profunda* is widely distributed in

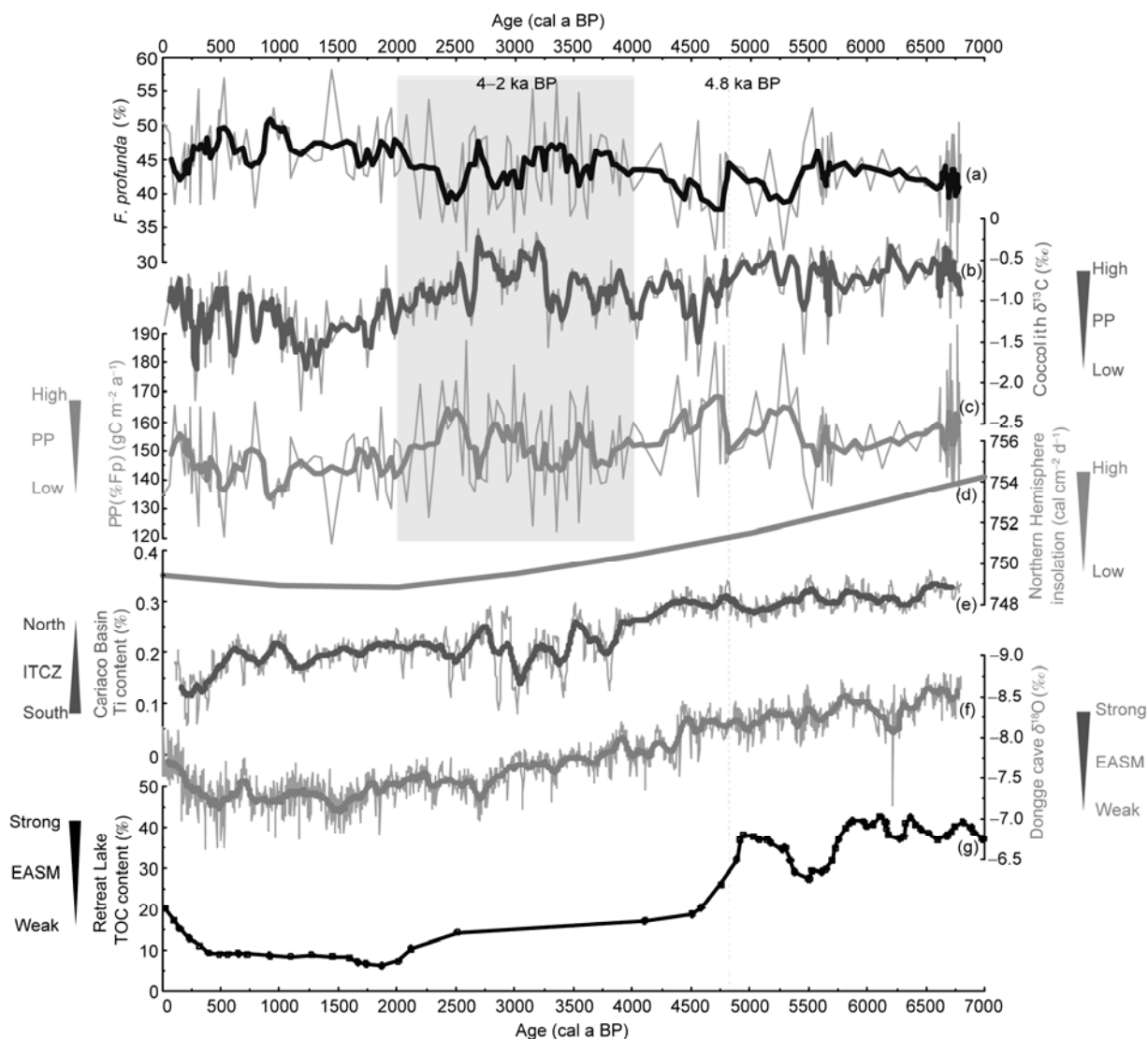


Figure 2 Variations of *F.p*%, coccolith $\delta^{13}\text{C}$, PP (%Fp) in MD05-2908, solar insolation in the Northern Hemisphere [37], Ti contents of the Cariaco Basin [38], Dongge stalagmite $\delta^{18}\text{O}$ [39] and TOC contents of Retreat Lake [17] over the last 6.8 ka BP.

the lower euphotic zone of the tropical-subtropical ocean [33], and its relative abundance is used to reconstruct oceanic primary production [34,35]. The relationship between the relative abundance of *F. profunda* and sea surface PP has already been quantified by Beaufort et al. [34] with the equation $PP = 617 - [279 \times \log(F.p\% + 3)]$, and the latitudinal range is the main limiting condition. Beaufort et al. [35] have successfully applied this equation to the Indian Ocean and the Pacific Ocean. Although core MD05-2908 (24.8°N) does not belong to the latitudinal range (20°S–20°N) of this equation, the southern Okinawa Trough has the characteristic of a strong, warm water source, so we tried to use the conversion equation to reconstruct the PP records. The PP (%Fp) value of the core top samples is $135 \text{ gC m}^{-2} \text{ a}^{-1}$, which is very similar to the estimated summer surface PP ($131 \pm 18 \text{ gC m}^{-2} \text{ a}^{-1}$) deduced from the measured data [21].

The PP(%Fp) changes between $118\text{--}193 \text{ gC m}^{-2} \text{ a}^{-1}$, with an average value of $151 \text{ gC m}^{-2} \text{ a}^{-1}$ (Figure 2(c)). The PP(%Fp) was relatively higher (average of $156 \text{ gC m}^{-2} \text{ a}^{-1}$) during 6.8–4.8 ka BP, which is consistent with the higher PP indicated by coccolith $\delta^{13}\text{C}$. After 4.8 ka BP, the PP (%Fp) increased first, then decreased and increased again, similar to the PP variations reflected by coccolith $\delta^{13}\text{C}$. It is noteworthy that both PP proxies showed high levels between 4–2 ka BP, corresponding to the Pulleniatina Minimum Event (PME) [10,36]. As shown in Figure 2(b) and (c), the PP reflected by the coccolith $\delta^{13}\text{C}$ and *F.p%* conversion equation in core MD05-2908 generally showed a fluctuating trend since 6.8 ka BP.

3.3 The impact mechanism of PP variations of the southern Okinawa Trough over the last 6.8 ka BP

Previous studies found that the sea surface PP evolution of the northern and middle Okinawa Trough is closely connected to the terrigenous input for the last 10 ka, and even the last 100 ka, and it may be affected by the EASM [40,41]. The core MD05-2908, located at the southern end of the Okinawa Trough, faces the Lanyang River delta of western Taiwan, north of which are the Jilong Valley, the Cotton Canyon and the north Cotton Canyon. These topographical features cause this area to easily accept terrigenous input material from the East China Sea shelf and Taiwan. Mineral and geochemistry indexes from adjacent core ODP1202 demonstrated that the provenance of this area was mainly the northeastern rivers of Taiwan since the Holocene [42]. Modern sedimentary dynamical observations showed that a large amount of eroded materials of Taiwan mountains was transported to the southern Okinawa Trough during the summer season [22]. In addition, a large amount of terrigenous materials was transported to the southern Okinawa Trough by the Taiwan rivers during the stronger EASM stage, which can induce stronger turbulence of the upper waters and the shallower nutricline eventually increasing the PP. Therefore, we believe that the PP records of the

MD05-2908 core are more sensitive to the changes of the EASM than other areas of the Okinawa Trough.

In the Mid-Holocene, the summer insolation of the Northern Hemisphere increased, leading to enhancement of seasonal contrast [43]. The numerical simulation results showed that the pressure gradient of the land and sea was enhanced by the strengthened Asian low pressure and the Pacific high pressure during the Mid-Holocene summer, which induced the stronger EASM [44]. In the Northern Hemisphere, the solar radiation of the Late Holocene decreased relative to the mid-Holocene (Figure 2(d)) [37], which should have weakened the capacity of pulling the ITCZ off the equator, inducing the southward shifts in the mean latitude of the ITCZ (Figure 2(e)). The EASM also weakened (Figure 2(f)) [39]. The TOC contents of Retreat Lake in Taiwan, near MD05-2908, indicated that the East Asian monsoon rainfall of the late Holocene was obviously lower than that of the Mid-Holocene (Figure 2(g)) [17]. The characteristics of the gradually weakening EASM since the Mid-Holocene have been recorded in many areas of the Asian monsoon region, such as the peat records of southern and northeastern China [45,46]; the stalagmite $\delta^{18}\text{O}$ records of Dongge cave in southern China and Shennongjia cave in central China [47,48]; and the pollen records of the Guangdong Huguang Maar Lake [49]. The EASM has weakened since the Late Holocene, reducing the terrigenous input of Taiwan rivers, and the upper water structure has become stable, resulting in the lower PP of this area. Our PP proxies of MD05-2908, including coccolith $\delta^{13}\text{C}$ and PP (%Fp), shows that the generally descending trend since the last 6.8 ka BP is consistent with the theory mentioned above.

The southern Okinawa Trough is located at the corner where the Kuroshio Current flows into the Okinawa Trough, and the hydrological conditions of the upper water are obviously influenced by the Kuroshio Current. The Kuroshio Current, originating from the Northern Equatorial Current, carries large amounts of high-temperature, high salinity and oligotrophic water, which can induce higher SSTs, a deeper nutricline and thermocline and a stronger PP.

The PP reflected by the coccolith $\delta^{13}\text{C}$ and *F.p%* conversion equation in core MD05-2908 showed high levels between 4–2 ka BP (Figure 2(b) and (c)), corresponding to the PME [10,36,50]. The weakening of the Kuroshio Current, representing the weakening of the Northern Equatorial Current and the trade winds over the equatorial Pacific Ocean, could induce the outbreak of El Niño. Geoarchaeological evidence from Peru indicates that ENSO activity strengthened after ~5 ka BP [51]. Storm deposition records from southwestern Ecuador proved that ENSO began in ~5 ka BP and a high-frequency of El Niño events appears at about 3.5–2.6 ka BP [52]. The SST gradient between the equatorial western and eastern Pacific of the Holocene reconstructed by foraminifera Mg/Ca has decreased since 4 ka BP, indicating the high frequency of El Niño events [53]. The SST of the tropical western Pacific dropped by 1.6°C from 5 to 2

ka BP [54], and the SST gradient between the equatorial western and eastern Pacific decreased, suggesting the prevalence of El Niño events. During El Niño, the interaction of the ocean-atmosphere induces the southern movement of the ITCZ [55], resulting in the weakening of the EASM. The weakening of the EASM during 4–2 ka BP is reflected in many records of the Asian monsoon regions, such as the intermittent deposition of Retreat Lake in Taiwan during 4.5–2.1 ka BP [17], the intermittent growth of the stalagmites of the northern Oman Hoti cave during 5.2–2.5 ka BP [56] and the low $\delta^{18}\text{O}$ values of the Shennongjia stalagmites in Hubei during 4.4–2.1 ka BP [57].

As discussed above, in the southern Okinawa Trough, the main controlling factors of the relatively higher PP during 4–2 ka BP is the weakening of the Kuroshio Current, not the reduced terrigenous inputs caused by the weakened EASM. During 6.8–4.8 ka BP, both PP proxies (coccolith $\delta^{13}\text{C}$ and PP (%Fp)) show higher values than those during 4–2 ka BP. As shown in Figure 2(d)–(g), the solar insolation is higher, the location of ITCZ is more northward and terrigenous inputs caused by the EASM are greater during 6.8–4.8 ka BP compared with during 4–2 ka BP. However, the long-chain alkenone data of MD05-2908 show that the SST during 6.8–4.8 ka BP is higher than that during 4–2 ka BP [58]. Previous studies have also demonstrated that the Kuroshio Current was stronger in the Mid-Holocene than in the Late Holocene [10,36,59]. This result shows that, compared with 4–2 ka BP, the relatively higher PP during 6.8–4.8 ka BP was mainly controlled by stronger terrigenous inputs caused by the strengthened EASM, and the effects of the Kuroshio Current are not obvious.

4 Conclusions

Based on 17 AMS¹⁴C age data, we reconstructed high-resolution sea surface PP variations in the southern Okinawa Trough over the last 6.8 ka BP using the coccolith $\delta^{13}\text{C}$ and $F.p\%$ conversion equation indexes. The PP showed a fluctuating decreasing trend since 6.8 ka BP, which was consistent with the reduced terrigenous inputs caused by the weakened EASM. The main controlling factor of the higher PP during 4–2 ka BP was the weakening of the Kuroshio Current. Compared with 4–2 ka BP, the relatively higher PP during 6.8–4.8 ka BP was mainly controlled by stronger terrigenous inputs caused by the strengthened EASM.

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